CHAPTER 17

RESEARCH ON RADIOACTIVE WASTE DISPOSAL IN THE NETHERLANDS WITH SPECIAL REFERENCE TO EARTH SCIENTIFIC STUDIES

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17.1 INTRODUCTION

Investigations for radioactive waste disposal in the Netherlands were carried out within the framework of the OPLA research programme (OPLA is a Dutch acronym for 'Disposal on Land'). The programme intended to explore the disposal options for nuclear waste in the deep subsurface below the Netherlands. Initially, the research focused on rock salt as a host rock.

Massive bodies of rock salt, with a thickness of 200 to 3,000 m, are present in the subsurface of the northern Netherlands. This potential host rock for radioactive waste disposal was deposited in layers about 220 to 250 Ma ago (the Zechstein period) by evaporation of a closed or semi-closed marine basin. After the evaporites were covered by fresh sediments, the layered salt started to flow at several places in the subsurface of the Netherlands. At many locations this resulted in the formation of salt pillows and sometimes, successively in salt diapirs. The tops of the shallowest salt diapirs rose to depths of about 100 m below the surface. The non-disturbed layered salt is situated generally at a depth of several kilometres below the earth's surface.

The OPLA research programme was divided into three phases for purposes of the interim parliamentary decision-taking procedure. At the end of each phase, government and parliament decide on the question of whether a subsequent phase of the programme is to be performed and, if so, what content and scope it should then have.

Execution of the first phase commenced in 1984. This first phase comprised a feasibility study, investigating various disposal methods and salt formation types with reference to safety. For that purpose, desk studies and laboratory investigations were performed on the basis of existing data in the public domain. In many cases, these investigations were carried out in international co-operation, for example in the area of *in situ* investigations. No decisions have been taken as yet regarding the execution of any further phases of the research programme, which will be more site-specific.

The OPLACommittee reported on the first phase of the research programme in mid 1989. A review of the first phase was given by Van Montfrans in the preceding issue (1991) of the present world-wide review. The conclusions of the studies undertaken in that programme amount, in brief, to a statement that safe disposal of radioactive waste in rock salt formations of a nature and scale as very probably occur in the Dutch subsurface is, in principle, feasible. The OPLA Committee also concluded that certain assumptions on which the conclusions were based required further verification to establish their reliability and accuracy. It was furthermore found that the possibility of identifying in concrete terms exactly which salt formations would be most eligible for further investigation on technical grounds was limited by a lack of site-specific data.

At the same time, according to the ILONA Committee (advising on the policy for radioactive waste management in the Netherlands) it was possible and necessary to perform supplementary research in order to reduce the limitations and margins of uncertainty established in a number of respects by the 1989 findings. This view was supported by the results of an international review performed by the European Community (EC) and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD). In addition, it was considered important that attention should be given to new developments, such as the retrievability of disposed-of waste.

17.2 CONTENTAND STRUCTURE OF THE SUPPLEMENTARY RESEARCH PROGRAMME

Based on the conclusions and recommendations of the first phase and the results of the EC/NEA review, the OPLACommittee formulated the main themes of a limited programme of supplementary research, “Phase 1A” (OPLA Committee, 1993). The most important themes are:

- Analysis and reduction of bandwidths in the results of Phase 1, particularly in the results of the safety analysis. This task invoked an improvement of the methodology of the Phase 1 safety approach. This approach was expanded into a methodology enabling systematic treatment of disposal risks. This improves the intercomparability of risks, and makes it possible to allow for probabilities of processes and data.
- In addition, careful analysis and further enlargement of the database on the subsurface was required. At the same time, the extension and further validation of the generic computer models applied in Phase 1 were dealt with. New models, describing the long-term geological evolution of the subsurface, were developed as well. The approach outlined above provides a better confirmatory basis for the findings of the safety study, and they may therefore be considered more accurate.
- Classification of salt formations for further investigation. Grouping of the salt formations was carried out on the basis of expected long-term stability and accommodation space for repository designs. This theme will not be discussed further in the present report.

At the same time, the Committee was requested to consider new developments; these are classed as a separate main theme. Two topics were dealt with in this theme, viz. the retrievability of disposed-of radioactive waste and the direct disposal of spent fuel elements.
Further, the Committee strongly advocated participation in international research programmes.

The supplementary programme was performed in the period from mid 1990 to mid 1993. Within the programme about 20 studies were performed in the areas of study of the OPLA research programme. These areas of study had already been considered in Phase 1: safety (the central theme), technical feasibility (mining engineering), geology and geohydrology, rock mechanics and radiation effects. This paper will deal with results of the supplementary programme and in particular will focus on the outcome of the various earth scientific background studies.

17.3 SAFETYANALYSIS

Progress was made on the following matters:

- risk assessment method; and
- data and models needed for the risk assessment.

17.3.1 Health risk assessment method

In Phase 1, the health risks of disposal were calculated on a deterministic and conservative basis, i.e. choosing circumstances unfavourable for safety and thereby overestimating risks. This approach hampered the inter-comparability of risks for the various disposal concepts in Phase 1. In addition, this method did not allow uncertainties and sensitivities to be treated in an adequate way.

Within the supplementary programme, a method was developed known as PROSA (PRobabilistisch Onderzoek aan de veiligheid van in Steenzout opgeborgen radioactief Afval = Probabilistic study into the safety of radioactive waste disposed of in rock salt), which accounts systematically for the probability of processes and subsurface data (Prij et al., 1993a). As a result, the risks as calculated are better confirmed and are more readily inter-comparable. The systematic treatment of uncertainties was incorporated within PROSA, thereby improving the significance of the sensitivity analysis as compared to Phase 1.

The PROSA method is essentially based on a system developed for the determination and selection of scenarios (possible situations in which radionuclides are released from a repository and can potentially reach the biosphere). The method is based on the internationally accepted multi-barrier system, which comprises three barriers:

- engineered barriers of the repository;
- rock salt around the repository; and
- overburden with aquifers and impermeable strata.

The degree in which this system acts as a barrier is affected by a complex of Features, Events and Processes (FEPs). These FEPs were used to construct scenarios relevant to conditions in the Netherlands. These scenarios can be subdivided into three classes:

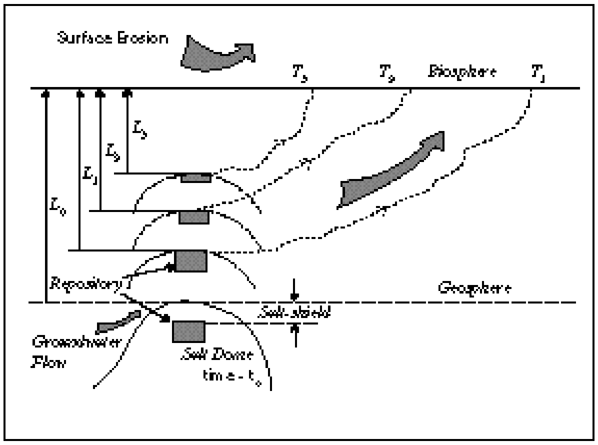


Figure 17.1. Schematic representation of the dissolution/diapirism scenario (Prij et al., 1993a).

- Subrosion/diapirism scenarios belonging to the category of normal evolution scenarios (Fig. 17.1). Gradual ascent of a salt dome (diapirism) brings it into contact with groundwater, salt dissolves (subrosion), radionuclides from the repository enter the groundwater and from there travel into the biosphere.
- Flooding scenarios belonging to the category of altered evolution scenarios. Groundwater penetrates into the repository, for example, as a result of fracturing or a water-permeable inclusion in the rock salt. Radionuclides and salt dissolve in this water. Convergence of the disposal chambers in the salt next forces the brine contaminated with radionuclides out of the salt into the groundwater. The radionuclides then enter the biosphere via the groundwater.
- Human intrusion scenarios belonging to the category of disruptive event scenarios. Various forms of mining engineering activities (exploratory drilling, construction of a mine) may bring future generations into involuntary contact with the waste (see also Prij, 1993).

Due to the lack of sufficient knowledge, two phenomena considered potentially important could not yet be fully calculated with the PROSA method: glaciation (the consequences of an ice age for the repository) and gas formation (consequences for the repository of gas formation near the waste resulting from thermal and radiation effects). Further, only those human intrusion scenarios were recalculated where improved insight relative to Phase 1 made it meaningful to do so.

In the supplementary programme, the risks were calculated for each of the above-mentioned scenario classes and for a number of schematised disposal situations in Dutch rock salt. The assumptions applied are based on the currently available data on the nature and size of rock salt formations as these very probably occur in the Dutch subsurface.

17.3.2 Data and Models Needed for Risk Calculations

Calculating the risk of subsurface disposal requires among other things a comprehensive database relating to the structure and the groundwater system of the subsurface. This database yields the necessary description of the multi-barrier system. For the purpose of the risk calculations, the processes involved in transporting radionuclides through this multi-barrier system are described by means of models.

The database built up in Phase 1 with published data on the subsurface was found to be limited in scale and usefulness. The supplementary desk studies therefore incorporated thorough analysis and enlargement of that geological and geohydrological database. This led to the determination of a number of bandwidths, for example, for spatial geological data on salt formations. In other respects, too, the precision of the data has been improved, for example, on the size of salt formations, rate of diapirism (Fig. 17.2, lower than had to be assumed in 1989), speed of dissolution processes of rock salt in ground water (Fig. 17.3, subrosion), structure and permeability of the rock surrounding the salt, and the mechanical behaviour of salt under the action of

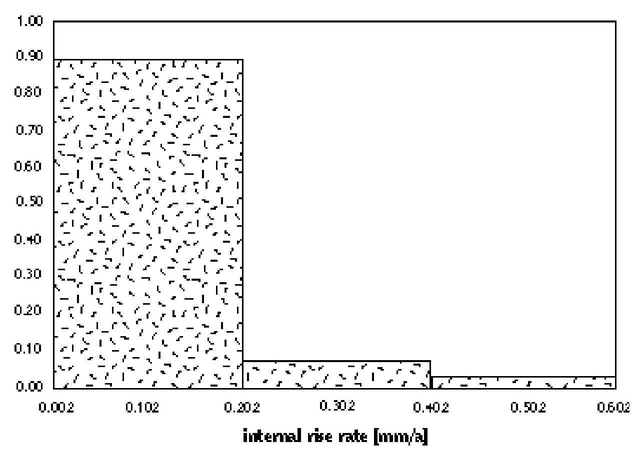


Figure 17.2. Probability density of the average internal rise rate for salt domes in the Netherlands and Germany (Prij et al., 1993a).

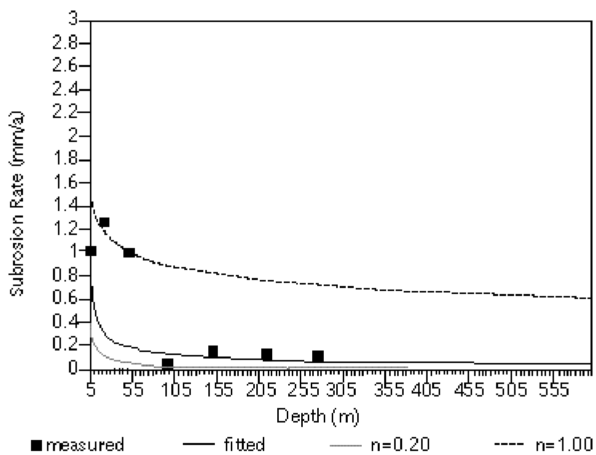


Figure 17.3. Input parameter of the depth-dependent subrosion rate. The measured values have been calculated for salt domes in Germany and the Netherlands with predominantly Quaternary subrosion activity. The upper line corresponds to a power-fit with exponent -0.2 and for the lower line this value is -1.0. The middle line with exponent = 0.64 has been used in the calculations (Prij et al., 1993a).

temperature effects. In addition, the database was supplemented with data on the subsurface which have become available by the geological mapping of the Netherlands and from geological exploration of the North Sea. This material also made a contribution towards improving the precision of the data.

In Phase 1, three important models were developed and applied for making risk calculations:

- release and transport model for radionuclides from the rock salt;
- transport model for radionuclides in the subsurface; and
- transport and exposure model for the biosphere.

These models underwent limited practical validation in Phase 1. Supplementary research proved the possibility of developing these - essentially generic - models further and validating them against a number of actual practical situations and data. For instance, the model describing the transport of radionuclides in rock salt was further confirmed with results from *in situ* experiments (the Asse Mine in Germany), i.e. under the action of such temperature and pressure as occur in an actual disposal situation. These results indicate that during the initial period of disposal, subsurface spaces in rock salt are closing by convergence more rapidly than was previously assumed. Further validation of this convergence process with reference to more practical data is needed in view of its great impact on safety.

In recent years, the model for radionuclides transport through the subsurface, named METROPOL, has successfully undergone comprehensive international validation in the INTRAVAL project (INternational TRAnsport model VALidation; Leijnse & Hassanizadeh, 1994; Van de Weerd et al., 1994; Van Weert et al., 1994; Leijnse et al., 1996 submitted). Comparison with other models within this project confirmed the reliability of this model. Its applicability to an actual situation was also demonstrated. For conditions prevailing in the Netherlands, this is supported by a case study on the Zuidwending salt dome (Oostrom et al., 1993).

The above-mentioned studies on processes and models and in particular the practical validation of these models have yielded greater clarity on the question of which data are needed for an adequate description of processes such as convergence, diapirism, subrosion and erosion.

17.3.3 Risks of Considered Scenarios

As stated above, by comparison with the approach in Phase 1 the present safety approach has yielded an improved insight into the uncertainties associated with the risks of geological disposal. The risks as now calculated are therefore to be regarded as more precise. Using the PROSA method to calculate the risks of the subrosion/diapirism scenarios yields values smaller than 10^{-9}/year. Similar risk values were found in Phase 1.

For the flooding scenarios, improved insights as compared to Phase 1 allowed modification of the rate of the process whereby subsurface spaces in rock salt are closing (convergence). The resultant radiation doses following dispersal of the radionuclides in the biosphere are found to be very low, and the associated risks much lower than as calculated in Phase 1, namely smaller than 10^{-10}/year.

The above-mentioned model modification for the convergence process in rock salt also has an important influence on the human intrusion scenario further considered (a leaking storage cavern near the repository).

The risks now calculated are significantly lower than Phase 1. For the human intrusion scenarios not analysed in PROSA, the risk appearing from the Phase 1 figures is smaller than 10^{-6}/year. Because large variations can occur in the transport of nuclides in the salt formation, in the overburden and in the biosphere, there is a large spread in the resulting risks calculated. Nevertheless, for all the scenarios considered the disposal risk remains smaller than 10^{-6}/year, and for "natural" scenarios (subrosion, diapirism, flooding) even smaller than 10^{-9}/year.

17.3.4 Risk Determining Features

Certain features of a repository and the geological barrier system around it may be determining for the risk of this particular facility. These features can be identified by determining the influence of all possible FEPs on the risk (sensitivity analysis). Phase 1 showed that the approach then used did not possess sufficient discriminating power to identify risk-determining features of a repository and the multi-barrier system. The principal drawback lay in the conservative approach and the uncertainty as to the extent thereof for each of the disposal situations considered.

Development of the PROSAmethod made it possible to eliminate this drawback by allowing a systematic approach and introducing the probability aspect. This makes it meaningful to perform a sensitivity analysis to identify risk-determining features of the multi-barrier system. From this sensitivity analysis, it follows that on the basis of the currently available limited database there are two features which predominantly determine the risk of the "natural" scenarios, namely:

- depth of the repository; and
- rate at which this facility is uplifted by possible diapirism.

To summarise, it may be stated that application of the currently available version of the PROSA method to a number of important scenarios and disposal concepts has proved extremely useful. In the first place, this system, as indicated above, provides an improved insight into the risks and uncertainties. Secondly, it helps, for example by means of the risk-determining features, to guide the direction of research in the various sub-areas of the OPLAprogramme.

17.4 TECHNICAL FEASIBILITY

In Phase 1, two different disposal techniques were studied:
- conventional (dry) mine, and
- deep boreholes drilled from the surface, in combination with caverns.

After study, it was concluded that both techniques are, in principle, technically feasible for salt formations in the Netherlands.

For the mine concept, the supplementary research programme provided further confirmation for that conclusion with the following findings:

- In co-operation with Germany, the practical feasibility has been demonstrated of a mine provided with deep boreholes, dry-drilled from a gallery to a depth of several hundred metres. These boreholes, intended for disposal of canisters with fission waste, constitute an important part of the mine concept.
- Within the same co-operative project, the practical development of a system for lowering, transporting and emplacing radioactive waste canisters in a disposal mine according to the German design has been successfully completed. In addition, the availability of a test facility for *in situ* investigation into rock salt has made a major contribution towards the acquisition of mining engineering experience (the HAW project in the Asse Mine; Prij & Hamilton, 1992; see also section 17.6.1).
- Important advances have been made with regard to technical feasibility, especially relating to the convergence process of rock salt (see section 17.6.1 for further information).
- As a result of the effects of radiation and heat, gas formation and radiation damage can occur in the vicinity of the radioactive waste disposed of in the rock salt. Conclusions regarding the significance of the two phenomena for mine design and disposal safety are still of a preliminary nature (see section 17.6.2 for further information).

With regard to the "deep boreholes from the surface combined with caverns" disposal technique, Phase 1 found that inspection of the reliability of the borehole and cavern seals was an item demanding special attention. In spite of supplementary literature research, no essential progress has been made in this area (Technische Universiteit Delft, 1993b). On the other hand, it has been found that the depth range of this disposal technique exceeds the range found in Phase 1. Depending on the diameter, depths down to around

3000 m are technically feasible with the deep borehole technique.

17.5 EARTH SCIENTIFIC BACKGROUND STUDIES

The major tasks of earth scientific research for radwaste disposal are the description of the present state of the geological barriers (site characterisation) and the prediction of the future state of the geological barriers in support of the scenario analysis.

The supplementary research in the areas of geology and geohydrology consists of two parts:

- improving data and models to support the risk calculations in the safety study (see also section 17.3); and
- increasing the basic knowledge which is needed for proper understanding of important processes in the subsurface. This item includes a number of subjects which emerged as recommendations from Phase 1, and which are not yet immediately applicable in the safety study at this time. Results will be discussed in this section.

17.5.1 Data Quality and Methods of Data Collection

Uncertainty Analysis of Available Geological Data

This research topic deals with the reliability of spatial geological data in general and more specifically with the depth values of geological horizons on contour maps and vertical profiles which are available for the research in the OPLA programme (Wildenborg et al., 1993). An uncertainty analysis of geological data was not carried out during Phase 1 of the OPLA programme.

For this analysis, the following approach was used; various sources of error are responsible for the differences in depth values between observed and real values. Those error sources are introduced by the acquisition of basic data (borehole data and seismic reflection data), by processing and interpretation and also during the construction of derived spatial data like contour maps and vertical profiles. After analysis of the various error sources involved, the magnitudes of the error sources are quantified in standard deviations of the difference between real and observed depth. Assuming mutual independence, all standard deviations of the sources of observation errors could be summed up to obtain insight in the total

$$s^2 = \frac{1}{n-1} \sum_n (z_w - z_e)^2 \qquad (1)$$

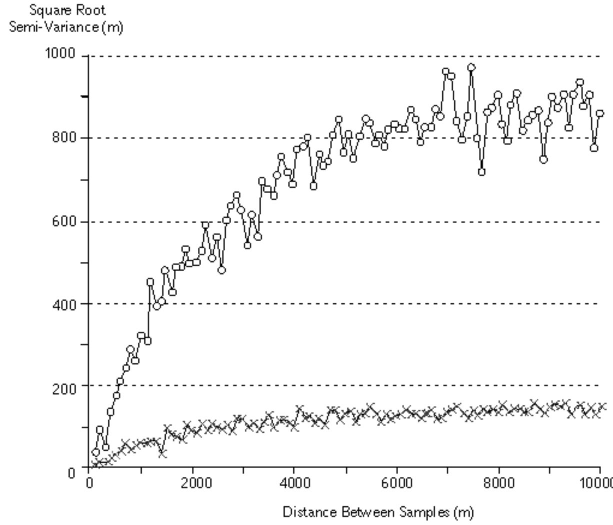


Figure 17.4. Semi-variogram of depth data derived from seismic observations.

standard deviation of the observation error :
where: s = standard deviation, z_w= observed depth,
z_e= expected depth, n= number of observations

This analysis was performed on derived spatial data, namely contour maps and vertical profiles (Fig. 17.4).

Borehole data and seismic reflection data are both used as original data for the construction of the spatial data mentioned. Borehole data are highly reliable. The standard deviation of the observation error of the depths to the base of the Tertiary and the top of the Zechstein are estimated to 2 m. Seismic reflection data are less reliable; the standard deviations of the observation errors could be as high as 125 m.

To construct a contour map, interpolation of the original data is necessary. Interpolation by itself is another source of error which increases with increasing distance from data points. The interpolation error also depends on the structural complexity (average dip) of the geological horizon). Using the estimations of the standard deviations of the observation error of borehole and seismic reflection data and the standard deviations of the interpolation error, it was possible to construct maps showing the place-dependent standard deviation of the top of the Zechstein around salt structures, and the base of the Tertiary above the salt.

Methods of Data Collection

Data on the shallow subsurface are available to a reasonable extent when it comes to investigating and modelling important geological and geohydrological processes for use in the safety study. When it comes to data on deeper formations, for example the composition and structure of rock salt and caprock, the rate at which salt dissolves in groundwater, salt concentrations in groundwater, and the diapirism rate of salt formations, they are inadequate.

The OPLA Committee therefore advised that two studies should be commissioned regarding the possibilities for collecting such data. One study concerned the development of equipment for the acquisition of reliable hydrological data at greater depth. An initial practical test has demonstrated the practicality of the technique chosen, and that it is suitable for further development

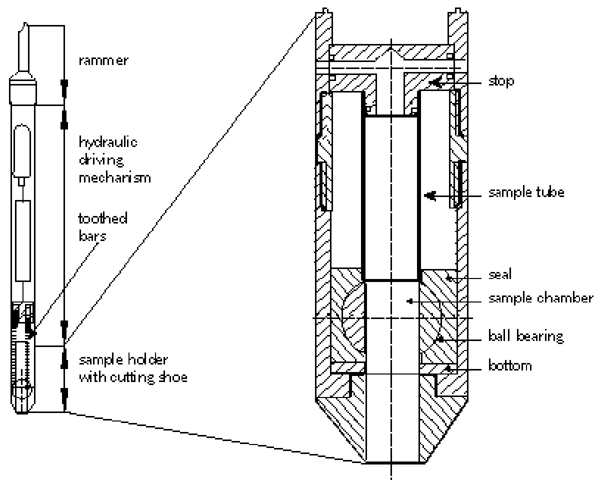


Figure 17.5. Apparatus designed for collecting geochemically undisturbed sediment samples in boreholes (Delft Ground Mechanics, 1993).

(Fig. 17.5).
Another study was focused among other things on the possibilities of advanced seismic methods in particular for the purpose of high-resolution determination of the depths and size of salt formations and the structure of the overburden (Table 17.1). Here, too, practical tests indicate that progress has been made.

Caprock Properties

Caprock refers to the rock which may be formed at the top of salt formations by the dissolution and removal of rock salt, while poorly soluble constituents remain and newly formed constituents are deposited. Knowledge concerning this rock is important because of the possible effects on mining engineering activities in or near caprock.

Aliterature study was performed in order to gain further insight into the processes which determine the formation and properties of caprock. That study made it clear that uncertainties still exist about the formation of caprock and the course of the processes relevant to it, and that little is known about the caprock of rock salt formations in the Netherlands. In a general way, it may be stated that it is important to allow for the properties of local caprock when constructing shafts.

A 6 m core section from the lowest part of the caprock was available from the Zuidwending salt dome. Detailed petrographic, geochemical and isotopic analyses were made of this core. The composition of the lowermost part of the caprock evidences a low salinity subroding brine. From the texture of the caprock it could be concluded that fluid flow was predominantly sub-horizontal. The lack of a vertical chemical gradient in the gypsum part of the caprock argues convincingly against any salinity gradient in the water in the caprock. Diffusion processes must therefore be regarded as insignificant.

17.5.2 Prediction of Future State of Geological Barriers

Long-term future predictions of the geological system are of great importance for the risk assessment of

Table 17.1. Resolution of various geophysical reconnaissance methods with depth in meters (Meekes et al., 1993).

Depth interval (in m)	Gravity Method	Geo-electrical method	Electromagnetic method	Seismic refraction method	Seismic reflection method
1-50	1-25	1-50	1-50	1-10	no signal
50-100	25-70	15-100	15-100	10-20	3-15
100-300	70-150	30-300	30-300	20-60	4-20
300-500	150-200	100-500	100-500	60-100	5-25

radioactive waste disposal. Abetter understanding of the physical and chemical mechanisms of the processes that affect the geological barriers, contributes significantly to a more reliable prognosis of the future state of the subsurface. For rock salt, three processes have been identified that may directly influence the geometry of the rock. These are salt movement, salt dissolution and erosion. Modelling studies have been performed to investigate their relation with the major climatic and geodynamic forces, and their effect on the geological barriers (Wildenborg et al., 1993).

The possible future states of the natural barriers are in general introduced as discrete scenarios in the safety studies. A drawback of this approach is that the total effect of all natural release scenarios is difficult to assess. Geological processes are in varying degree coupled to one another, which makes it difficult or even impossible to split the system in several autonomous compartments. Therefore, it is advisable to pursue an integrated approach parallel or complementary to the scenario method, in which the whole natural barrier system, the processes inclusive, is considered as one entity.

An example of a coupled system is the relation between climatic processes and surface or near-surface processes. Our knowledge of the impact on geologic disposal of recurrent ice ages, induced by climatic changes, has been substantially expanded (Wildenborg et al., 1990). The geological cycles concerned are relatively short, with a length of about 100,000 years, and have almost completely dominated the surface or near-surface processes in Northern Europe for the past one million years. This knowledge, based on comprehensive observations of deposits formed during a number of past cycles, makes it possible to model a large part of these processes in their relevance to the disposal issue. This holds especially for the effects of salt dissolution and erosion on the salt barrier.

Barrier Model

A geological barrier model ideally should simulate the future evolution of the barriers over a period of 10^5 to 10^6 years, should comprise physical and chemical formulations of all relevant processes that directly or indirectly affect the future barrier state and is driven by time-dependent climatic and tectonic forcing mechanisms. Since the beginning of the eighties, various models have been developed to simulate the future behaviour of the geological system in connection with radioactive waste disposal, e.g. GSM and FFSM in the United States, CASTOR in France and TIME4 in Great Britain.

Central in the barrier model to be developed is the local submodel describing the geometry and the properties of the various geological barriers around the disposal facility. The locally operating processes like salt dissolution, salt movement and erosion are incorporated in this part of the model. The climatic and geodynamic boundary conditions are generated in supraregional submodels on the scale of NW Europe or on an even larger scale. Geological observational data have to be gathered in a systematical way to provide input data for the model and data for extensive testing of the model output (Wildenborg et al., 1995).

The mechanisms of the processes that may directly affect the salt barrier (Fig. 17.6), have been studied in detail and will be discussed briefly here.

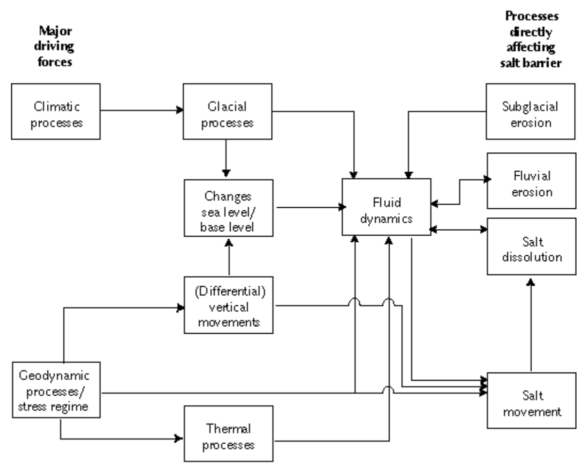


Figure 17.6. Relation diagram of the major processes to be incorporated in the geological barrier model. Note that only part of the pertinent relations between the processes have been marked in this diagram.

Process of Salt Movement

Observations in the Netherlands on- and offshore region show that salt structures are geographically related to faults in the salt basement (Remmelts, 1996; see also Fig. 17.7). The timing of salt movement is related to tectonic phases. For example, the average rise rates of salt structures during the early part of the Oligocene, a period of tensile intra-plate stress, were three to five times higher than during the Late Tertiary and Quaternary, which period was governed by compression.

The role and timing of changes in intra-plate stress also

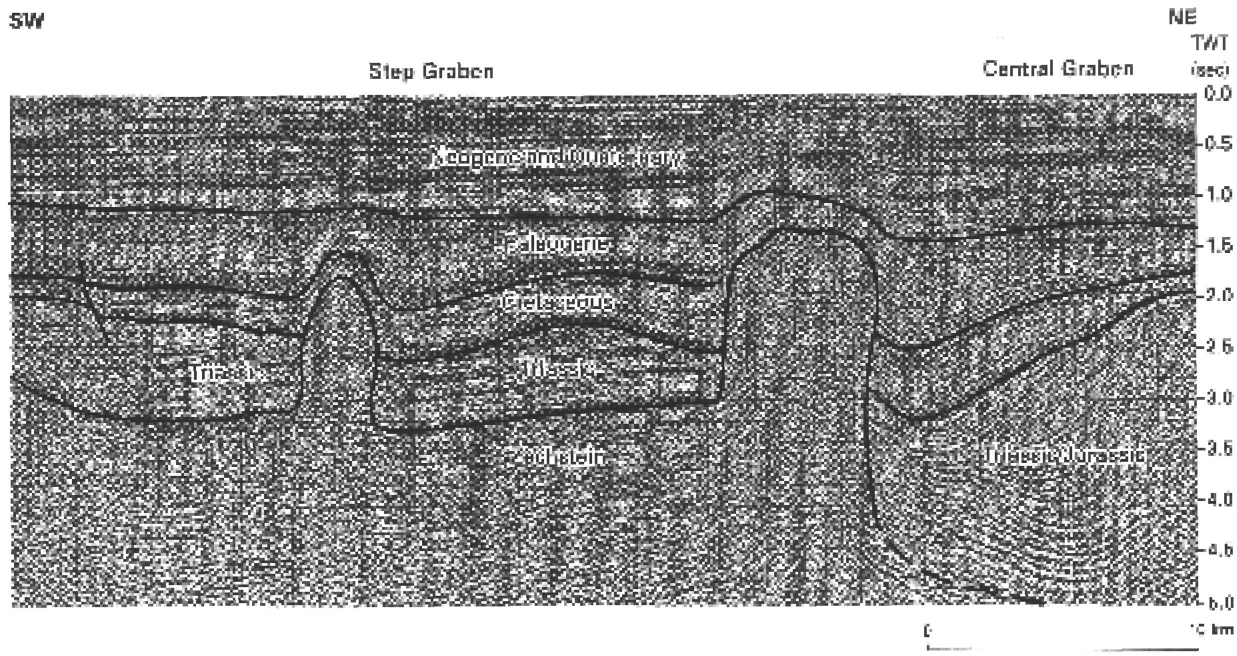


Figure 17.7. Seismic section across salt structures in the offshore region of the Netherlands.

appears on a basin-wide scale. An increased level of compressive stress during the Late Neogene in the North Sea basin is reflected in high subsidence rates. These high rates can not be explained only by the classical lithospheric stretching-cooling model of McKenzie (Cloetingh & Kooi, 1992). Increased rate of uplift during the Late Neogene has been reconstructed for peripheral parts of the North Sea Basin (Van den Berg et al., 1996 submitted). The change in stress level probably is related to important plate-boundary reorganisations. The compressive stress regime is still dominant at present in Northwest Europe (Müller et al., 1992). It is marked by a NW-SE direction, related to the Africa/Europe collision and to ridge-push forces operating in the northern Atlantic.

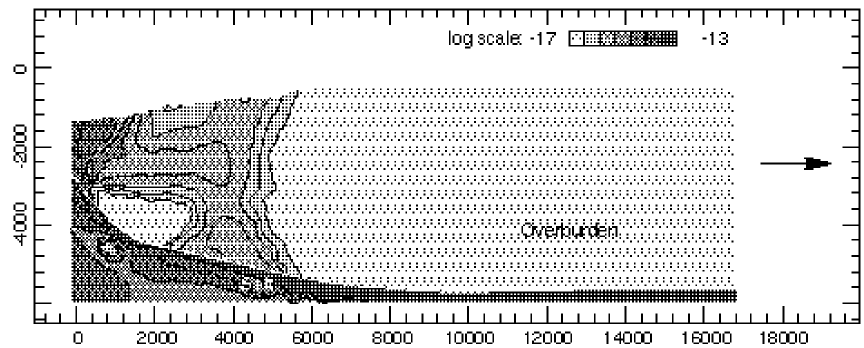
The effect of intraplate stress on salt movement has been investigated in numerical model studies (Daudré & Cloetingh, 1994). The numerical experiments have been carried out with a two-dimensional planar model of a visco-plastic salt layer and a brittle overburden. Three tectonic scenarios have been investigated: one in which buoyant forces are the only driving mechanism, one in a tensile stress regime and the last with a compressive stress regime (see also Fig. 17.8).

The first modelling experiment has revealed that buoyant forces are too weak to overcome the yield strength of the overburden. Diapiric movement of the salt occurs in a tensional regime with the simultaneous development of shear bands in the overburden. The modelling for a regime of compressional intraplate stress has shown a more modest salt movement and the development of various systems of shear bands.

These results strongly suggest that the classical theory of a gravitational drive for the initiation of salt movement probably does not hold. It appears that regional tectonic forces are a prerequisite for the start of salt movement. The most favourable situation for the initiation of salt movement is a tensional regime; re-activation of diapirism under compression appears to be quite important.

A better understanding of the rheological properties of the overburden is necessary for a more reliable simulation of diapiric deformation. Better understanding of the dynamics of salt diapirism obviously depends on better constraints on the interplay of fluid flow and the initiation of diapirism on a basin-wide scale. Especially, the experiments with compressive stress need further attention, since the fluid pressure in the sedimentary rocks increases significantly in a compressive regime (Van Balen & Cloetingh, 1993). Fluid pressure in rocks is a major factor in determining the rheological properties of the rock. More attention should also be paid to the effect of sedimentation and erosion on the development of salt diapirs (Poliakov et al., 1993).

Process of Salt Dissolution and Climate-Induced



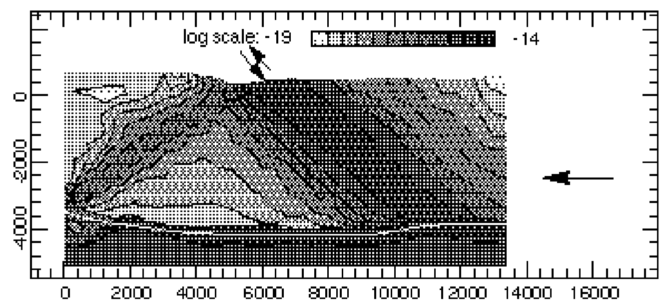


Figure 17.8. Results of mechanical modelling of diapirism. Above: Strain rates after 30 Ma in a tensile regime; strain rates in the range of log(10^{-17} - 10^{-13}/s). Below: Strain rates after 25 Ma in a compressive regime; strain rates in the range of log(10^{-19} - 10^{-14}/s) (Daudré and Cloetingh, 1994).

Hydrological Changes

The dissolution of salt diapirs is primarily controlled by the amount of available groundwater around the salt structure and the solubility and dissolution rates of the evaporite minerals present in the salt dome. In turn, these parameters are controlled by a complex set of other, frequently interrelated parameters such as temperature, pressure, fluid flow composition (i.e. the undersaturation of the groundwater with respect to NaCl), and the permeability of the surrounding sediments. Effects of temperature and pressure on dissolution rates and solubilities are well known from the literature. Subrosion rates as well as solubilities increase with fluid flow velocity and temperature. Since fluid flow velocity is the dominant effect and flow velocities in aquifers in the northeastern Netherlands rapidly decrease with depth, subrosion rates of salt diapirs are expected to decrease rapidly with depth.

The effects of climatic change on groundwater flow and consequently on subrosion at the top of diapiric structures have been investigated and modelled on different scales (Edinburgh University et al., 1996 in prep; Oostrom et al., 1993). Hydrogeological and (palaeo-)environmental data sets have been prepared for application in groundwater flow and subrosion models for:

- the salt-tectonically disturbed subsurface of the north eastern Netherlands for which a regional model and a local model have been developed in a joint project called SESAM in which the Geological Survey of the Netherlands (RGD), the Dutch National Institute of Public Health and Environmental Protection (RIVM) and the TNO Institute of Applied Geoscience participated (see also Fig. 17.9. Van Gijssel, 1995).
- the Cainozoic and Mesozoic subsurface of the Northwest European lowlands, in the scope of an EC-funded, joint project of the University of Edinburgh, RGD, RIVM and the University of Paris-Sud and the Catholique University of Louvain-la-Neuve (Boulton et al., 1993).

Glacial cycles associated with ice sheet expansion and permafrost conditions beyond are believed to have had a major impact on the groundwater flow patterns and hence subrosion rates. In order to approximate this impact, a time-dependent, thermo-mechanically coupled

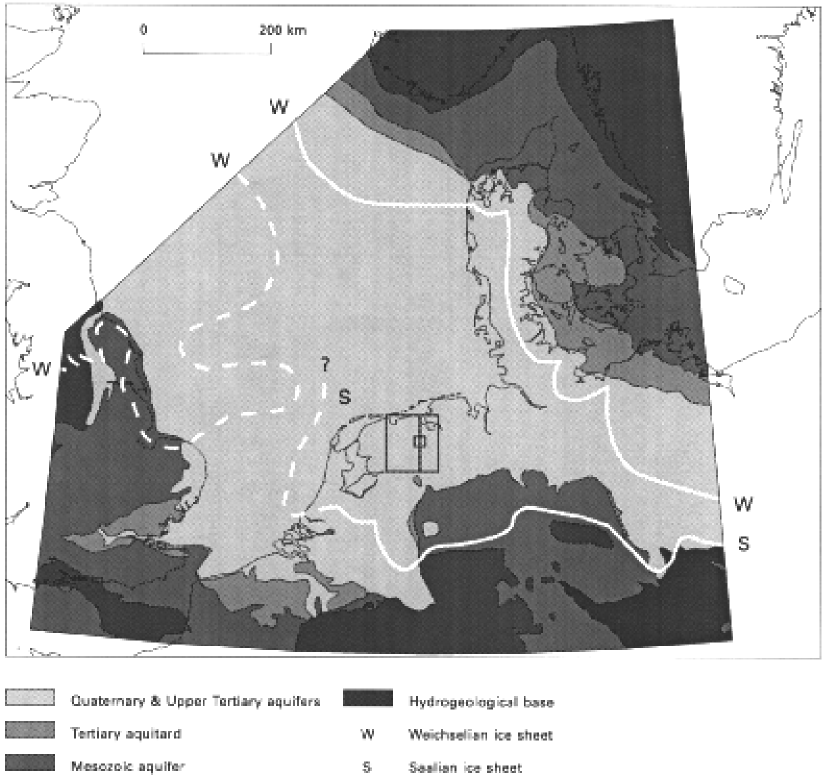


Figure 17.9. Location of the local and regional model areas in the northeastern Netherlands used for the simulation of salt dissolution and the boundaries of the major ice advances in the Late Quaternary. The major part of the Zechstein salt structures in the Netherlands are present within the regional model area.

flow line model has been developed in the EC-funded project and applied to a supra-regional transect from South Sweden to northern France, so as to match the inferred Weichselian and Saalian glaciations (Boulton & Van Gijssel, 1996). A general subglacial groundwater flow model for NW Europe, consisting of several components and interfaces (an ice-sheet model, a sea-level model, a large-scale groundwater flow model and a subrosion model for rock salt) has been applied to a large number of potential geological situations (Van Weert et al., 1996). The simulations corroborate the importance of the regional hydrogeological conditions and the permafrost distribution beyond the ice sheet margin in controlling ice and groundwater flow.

Drainage and topography have been dramatically changed by the subsequent ice sheet advances. The northward flowing rivers in northwest and central Europe responded by changing their courses in a westerly direction. Lakes that were impounded by glacier ice often drained suddenly, in particular during the deglaciation of the ice sheets and melting of the permafrost. Palaeo-channels formed by abnormally high discharge events are frequently found in the subsurface of the marginal zones of the Pleistocene ice sheets. Deep and penetrative flushing of aquifers by glacial meltwater may have lead to increased subrosion rates of salt diapirs in contact with these aquifers.

The large-scale flow boundary conditions provided by the EC-funded project have been used in the regional and local model simulations for the northeastern Netherlands, carried out in the scope of the SESAM-project, which was focused on one salt diapir only. On the basis of the schematic geometrical frameworks and averaged values of the geohydrological parameters, numerical hydrological models have been reconstructed to evaluate the groundwater flow systems and subrosion rates in the vicinity of selected salt structures in the northeastern Netherlands. The simulations have been concentrated in the first instance on present-day boundary conditions.

In order to investigate the effects of climate change on the groundwater flow patterns, subsequent modelling experiments have been performed using estimated

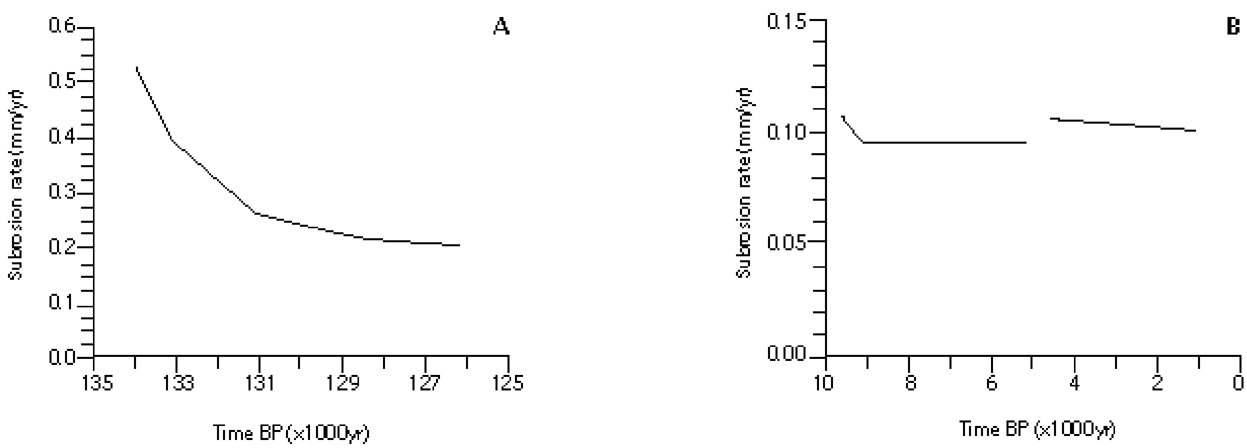


Figure 17.10. Simulated subrosion rates for different time spans. A. Late Saalian ice-free periglacial conditions; B. Interglacial conditions; 2-D simulations, heterogeneous flow field, permeability $k_{65}=10^{-14}$ m^2 (Oostrom et al., 1993).

hydrological boundary conditions for relevant time intervals during the Late Quaternary. Regional 3-D groundwater flow simulations on the basis of reconstructed isohypse maps for different post-Saalian, steady-state time intervals in the ice-free area of the northeastern Netherlands clearly indicate the effects of changing climatological conditions on the upper groundwater system (Oostrom et al., 1993). Groundwater flow velocities were a factor two higher in the period following the deglaciation of the Saalian ice sheet as a consequence of large differences in relief and low sea level stands. Subsequent relief levelling and sea level rise during the Eemian interglacial led to low potential gradients and hence resulted in low groundwater flow velocities. Groundwater flow velocities during the Weichselian cold stage with periglacial conditions, were similar to those during the interglacial periods.

Using these regional boundary conditions for a local model, simulating the subrosion rates at the top of a selected salt diapir by the METROPOL-3 code (finite element mesh: Sauter et al., 1990), showed the influence of the magnitude of the groundwater flow velocities near the salt diapir on the subrosion rate. The subrosion rates simulated for the Late Saalian period are found to be substantially higher than for the other periods (Fig. 17.10). Significant differences in subrosion rates between the interglacial periods and the Weichselian time intervals with permafrost conditions, could not be assessed. The input parameters for the sensitivity analyses, such as permeability and anisotropy ratio, show that the resulting range in the simulated groundwater flow velocities and subrosion rates exceed the values calculated for the past.

The subrosion simulations in many ways are simple representations of natural conditions, particularly the 2-D simulations. Since testing of the models used is not possible, because adequate field data and predictions covering thousands of years are lacking, emphasis has been put on calibration for present-day conditions, detailed sensitivity analysis, groundwater flow simulations of past time intervals (which are not necessarily similar to future observations) and comparison of calculated subrosion rates with values known from the literature.

Process of Fluvial Erosion

Fluvial erosion and sedimentation are the results of complex process interactions. Quaternary fluvial dynamics in the Netherlands are mainly governed by the combined effects of sea-level fluctuations, tectonics and climatic change. In addition, and dependent on the space and time scales used, a fluvial system can be controlled by other more local factors and processes (Wildenborg et al., 1993). These complex interactions of processes and factors within the fluvial system were integrated within the model FLUVER (Veldkamp & van Dijke, 1994). FLUVER is a finite-state model using quantitative and qualitative relationships of fluvial systems acting over a long time span (500 ka). Model construction, o rganisation, operation and testing are extensively described in previous papers (Veldkamp, 1991; 1992). FLUVER simulates the evolution of a fluvial landscape by both sedimentological and erosional processes as controlled by relief, climate, tectonics and fluctuations

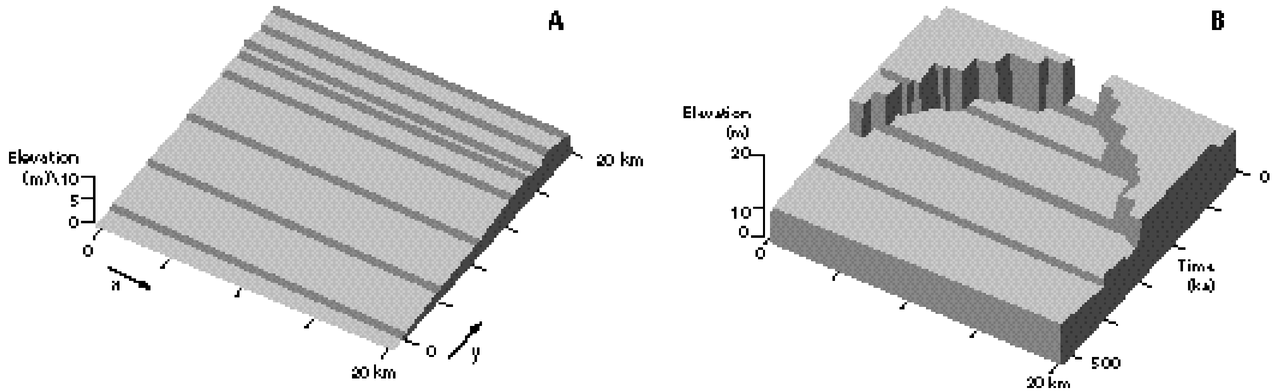


Figure 17.11. Simulation of fluvial landscape in a tectonic subsidence scenario. A - Dynamic evolution of a cross-section through time; B - Landscape after 500 ka.

in base-level of erosion (sea-level changes). The model processes are long-term and large-scale analogies of real erosion and sedimentation processes which react to changes in the climate controlled discharge-sediment load equilibrium which is calculated for time steps of 2 ka each. Both two ka discharge and two ka sediment load are assumed to be a function of climate change as described by the astronomical parameters of Milankovitch theory. Furthermore, both relationships are supposed to be out of phase (Veldkamp, 1991; 1992).

When sediment-input load would exceed the sediment transport capacity, the excess volume will be deposited, and in case the transport capacity exceeds the input load the difference is eroded in the simulated system. The zone with active erosion migrates headward along the longitudinal profile, while the sedimentation zone migrates in a downward direction. Except for changes in climate the simulated fluvial system also reacts to changes in base-level of erosion and vertical crustal movements. In case of uplift or lowering of the base-level of erosion, the fluvial system will strive to compensate by erosion, which is not always possible since climatic conditions may be such that the simulated systems tends to deposition. A similar relationship applies for crustal subsidence and rise of the base-level of erosion which will stimulate sedimentation in the simulated system.

Several simulation runs were made, demonstrating that vertical fluvial erosion in the Netherlands is strongly controlled by sea-level fluctuations and vertical tectonic movements. An example of the simulations with tectonic subsidence is illustrated in Figure 17.11. The tentative conclusion is that during the next few hundred thousand years, fluvial erosion will probably not affect buried salt structures, assuming that climate and change in the base-level of erosion can be satisfactorily described with the Milankovitch theory, tectonic activity in the Netherlands will not change considerably and that no larger fluvial systems than the Rhine or Meuse will enter the Netherlands.

Although reliable long-term input for future conditions is lacking and FLUVER simulations have conceptual validity only, FLUVER can demonstrate potential long-term fluvial erosion effects. To arrive at a more quantitative reliable model, it will be necessary to collect more quantitative data on site-specific fluvial records. Since this model study was mainly based on general data, a comparison and evaluation with actual field data could also improve model performance. Extended and well dated fluvial records of subsiding and uplifting regions like fluvial basin infills and fluvial terraces may serve as a primary data set to which FLUVER or similar models could be tuned. A first tuning exercise was done for the Meuse terraces at Maastricht (Veldkamp & Van den Berg, 1993). As long as extensive testing exercises have not been carried out FLUVER has no reliable quantitative forecasting status.

Process of Subglacial Erosion

From the variety of erosional features related to glacial activity, the formation of very deep tunnel valleys is undoubtedly the most important with respect to the stability of the geological barrier (Wildenborg et al., 1993). Very deep tunnel valleys in northwestern Europe of Elsterian age where analysed on their geometry and pos-

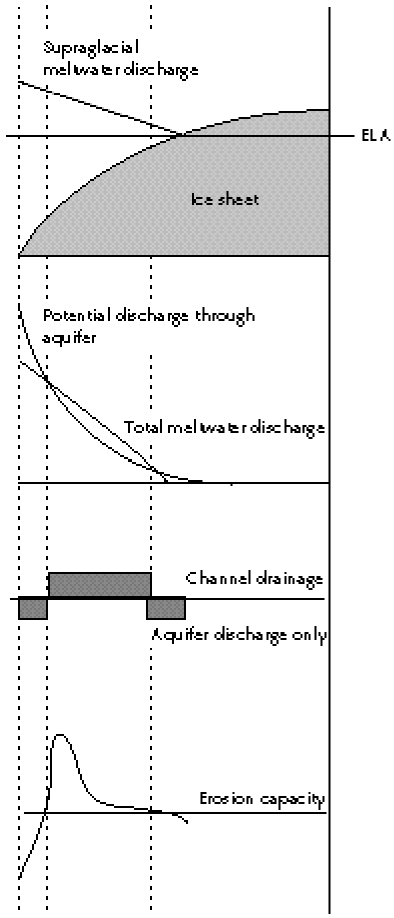


Figure 17.12. Graphical presentation of the conceptual model SUBGLER. ELA = equilibrium line altitude. Below ELA supraglacial meltwater is produced which is assumed to be added to the subglacial meltwater. Drainage through subglacial channels and subsequent erosion occurs if the production of subglacial meltwater is larger than the discharge capacity of the underlying aquifer.

sible genesis in order to define tunnel-valley process conditions. Mathematical translation of the formation processes were subsequently used for the construction of a computer simulation model (SUBGLER). The aim of the model construction is the prediction of the erosional effects of a future glaciation in the Netherlands.

In accordance with generally accepted theories concerning the development of tunnel valleys, SUBGLER simulates the longitudinal one-dimensional flow of meltwater in subglacial channels under glaciostatic pressure (Nye, 1976; Shoemaker, 1986; Boulton & Hindmarsh, 1987; see also Fig. 17.12). Furthermore, sediment transport functions were developed to relate erosion to the amount of subglacial melt water.
Model construction demonstrated that subglacial channels under a large continental ice sheet overlying an area consisting of a thick sandy aquifer, comparable to the pre-Elsterian conditions in the Netherlands, are only to be expected during the last phase of a glaciation. During this phase, large volumes of supraglacial melt water are assumed to be added to the subglacial system (Jeffery, 1991). The incorporated influence of supraglacial meltwater makes the model sensitive to climatic changes during deglaciation.

Preliminary modelling conclusions after several test runs are based on the individual contribution of various selected input parameters (see also Fig. 17.13). The relative significance of the input parameters are (in decreasing order of importance): mean summer air temperature at the ice sheet margin, longitudinal ice sheet profile, rate of ice sheet margin retreat, and hydraulic conductivity of the aquifer.

The simulations suggest that deep glacial erosion can be expected during any future glaciation, but no reliable estimations can be given on their maximum theoretical depths. In order to allow more precise simulation of future behaviour of subglacial systems, considerable geological field data on Quaternary tunnel valley formation is required. More information is needed on water pressures in subglacial aquifers, sediment loads in subglacial channels and the contribution of supraglacial meltwater to the subglacial system. Current research on the subglacial hydrologic system shows that modelling of groundwater flow within the vicinity of subglacial channels enables a more precise assessment of maximum depths of tunnel valleys (Van Dijke & Veldkamp, 1995).

17.6 INTERACTION BETWEEN WASTE AND HOST ROCK

17.6.1 Effects of Changes in Temperature and Stress

The behaviour of rock salt as host rock under the action of temperature and pressure was comprehensively studied in Phase 1, both *in situ* (the Asse Mine) and in the laboratory (Prij et al., 1995). In the supplementary research programme, the study into rock mechanics was concentrated on a continuation of the *in situ* investigations. Results obtained in that context concerning the

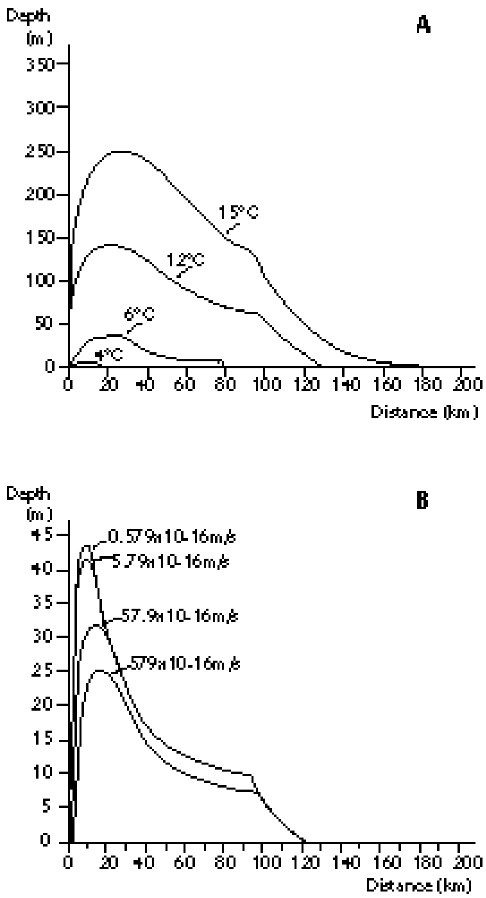


Figure 17.13. Results of the simulations with SUBGLER. A. Effect of changes in air temperature; B. Effect of changes in hydraulic conductivity.

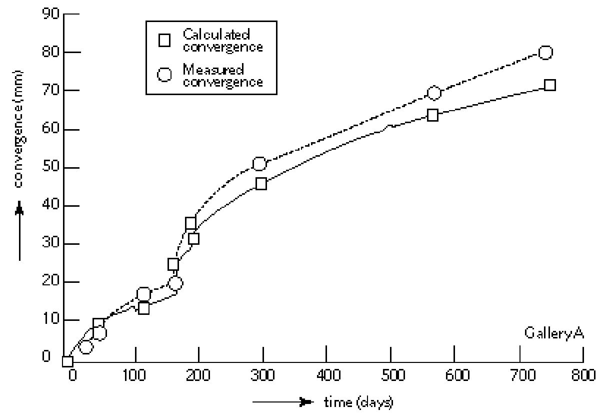


Figure 17.14. Convergence in the mining gallery in the HAW-experiment (Prij et al., 1993b).

convergence process of rock salt, which are important for the safety studies, have yielded an increased understanding of this time-dependent process in geological spaces. The convergence process initially proceeds faster than was previously assumed, but after some time it proceeds much more slowly (Fig. 17.14; Prij et al., 1993).

Further modelling of the thermomechanical behaviour of rock salt and practical validation of the models against measurement results have improved the reliability of these models. This made it possible to improve the quality of predictions on the behaviour of a subsurface disposal space under the influence of temperature and pressure. This is important for any modifications and optimisation of repository designs.

The Netherlands Energy Research Centre (ECN) is co-operating with German, French and Spanish research institutes on a number of joint *in situ* projects in the Asse Mine (ECN, 1993b; Prij & Hamilton, 1992; Heijdra & Prij, 1996, in prep). One of those projects, the High Active Waste (HAW) project is a demonstration project for the disposal of high-level radioactive waste. In particular, the interaction between salt and thermogenic waste is being studied here in a practical situation.

17.6.2 Radiation Effects

Disposed-of waste produces radiation. This radiation can cause abnormalities (damage) in the crystalline structure of the rock salt. As a result, energy builds up in the damaged salt, and later it can potentially be released. The results of the Phase 1 research showed that the build-up of radiation damage in salt depends strongly on the presence of certain natural contaminants, such as potassium, bromine, lithium, etc. Uncertainty as to the maximum level of radiation damage under disposal conditions meant that the Phase 1 calculation of the effects of energy release allowed for a damage rate of several tens of percentage points. On the basis of preliminary calculations and assuming a spontaneous and total energy release, these consequences were found to be very limited in scale and did not lead to the release of radionuclides from the salt.

Supplementary laboratory investigation has yielded a number of fresh results (Groote et al., 1991; Seinen et al., 1992; 1995; Garcia Celma et al., 1993). The complexity of this subject matter was such that new questions arose which have not yet been answered. These questions concern the initial stage of the damage, the form and dimensions of the damage nuclei (the colloids) and the influence of such factors as temperature, radiation dose, dose rate, pressure, deformations and natural contaminants (Prij, 1996a, in prep a; Garcia Celma et al., 1995). Insight into these is needed to improve the calculation model that predicts radiation damage under disposal conditions. The foundation for the calculation model was laid by Jain and Lidiard, and in that form it was applied in Phase 1. Progress has been made in the matter of model development, but uncertainties have continued to exist as well, for instance with regard to the causes of the action of contaminants on the damage level.

Laboratory investigations into the properties of strongly irradiated salt (up to radiation doses 6 times higher than under disposal conditions) has shown that, under certain conditions, the damage can rise to around 10%. It has furthermore been found that higher doses are capable of causing even more damage (Rijksuniversiteit Groningen, 1993; Weerkamp et al., 1994).

In some cases, a very rapid reaction was observed, taking an explosive course. Further investigation into the nature of the release process is underway. The significance of this process under disposal conditions merits special attention.

Since Phase 1, good progress has been made with modelling the effects on the surrounding rock salt of the above-mentioned release, capable of allowing for a spontaneous, very rapid and total release of all the energy built-up with radiation damage. The approach taken, which is still subject to scientific debate concerning the release rate and the accompanying temperature rise, broadly confirms the conclusion as drawn in Phase 1 that the effects of sudden energy release would be very limited (ECN, 1993a; Rijksuniversiteit Groningen, 1993; Prij, 1996; Prij, in prep b).

In view of the above, it appears meaningful to continue the investigation into the consequences of radiation damage for disposal safety. For that purpose, the chemical stability of salt and glass, as well as design engineering aspects relating to the repository, can play an important role.

17.7 ALTERNATIVE DISPOSAL CONCEPTS

Current developments in the public interest sphere demanded attention for the following subjects:

- retrievability of disposed-of radioactive waste;
- direct disposal of spent fuel elements.

In an exploratory way, it was examined whether these developments can be integrated in the Phase 1 disposal concepts at the technical level. Their effects, if any, on disposal safety have been considered as far as possible.

17.7.1 Retrievability of Disposed-of Radioactive Waste

Discussions held in wider context and, among other things, an OPLA preliminary study into retrievability disclose a central question: what is envisaged with retrievability? A number of considerations differing widely in nature may be relevant. At any rate, it must be borne in mind that accessibility of disposed-of waste is time-related. Although mining engineering measures make it possible to extend the period of this accessibility to, possibly, some hundreds of years, nevertheless it is impossible to extend it indefinitely. This is because a geological facility is designed for isolation over very long periods, of an order of magnitude of 100,000 years. In that term, of course, retrievability cannot be guaranteed. The question then arises, how is retrievability to be viewed in this context?

All in all, these considerations must be carefully dealt with in a generic study. To that end, an initial step has been taken in carrying out a general EC study, on Dutch initiative, dealing with economics, mining engineering and various host rocks. This study, which is not part of the OPLA programme, is still in progress (Prij & Heijdra, 1995; Heijdra et al., 1996, in prep.).

Quite apart from the above, it is worthwhile considering what mining engineering options are currently available to accomplish a certain measure of retrievability (Technische Universiteit Delft, 1993a; Van den Broek et al., 1994). The investigative OPLAresearch programme indicates that, in a general sense, retrievability is technically feasible but that this requires the Phase 1 mine concept to be modified in a number of respects. In particular, these modifications include a reduction of the length of the boreholes drilled from the galleries, and a reduction of the thermal effect, in order to keep the waste accessible as easily as possible and for as long as possible. The study also reports that certain concepts for "direct disposal" of spent fuel elements as studied for example in Germany can be readily combined with possible retrievability of the waste. For this purpose, use is made of highly robust "Pollux" containers, which are disposed of in galleries in a mine.

Although the OPLA study is not intended to assess the measure of accessibility for predetermined periods, based on preliminary findings the period refers to a retrievability term of several hundred years, the period during which full information will be present concerning the location of the waste. In the longer term, a situation is envisaged in which the repository has been closed by polydimensional rock pressure and the waste can only be recovered by means of "remining". Underground geophysical survey methods will be able to provide guidance in this case.

The investigative OPLA programme made no statements on the safety aspects of retrievability.

There is no clarity as to the objectives of retrievability. There are a number of possible replies to the question of what is primarily envisaged with retrievability. Different objectives can lead to different mining engineering consequences, each with their own consequences for the "terms of guarantee" and longer-term safety.

17.7.2 Direct Disposal of Spent Fuel Elements

In Phase 1 of the OPLA research programme, it was assumed that, in accordance with the present situation in the Netherlands, spent fuel is reprocessed into re-usable fissile material. The reprocessing waste produced in that process (including the fission waste) form an essential component of the total radioactive waste flow to be disposed of. Developments in the sphere of public interest are calling attention to a fuel cycle without reprocessing. Anumber of countries (the United States, Sweden) have in the past for various reasons opted for the non-reprocessing route. In such a situation, therefore, it is not processing waste but spent fuel material that has to be disposed of.

The consequences of this for safety and for repository design have for some time been the subject of studies in other countries. For instance, the German Projekt Alternatieve Entsorgung (PAE) investigates two techniques for direct disposal. One technique, which is regarded as the most important, is based on large, thick-wall steel containers in which the entire spent fuel elements are disposed of. These "Pollux" containers are emplaced in galleries in the salt formation, after which the interjacent spaces are backfilled with crushed salt. This method differs essentially from the mine concept with vertical boreholes in the galleries, as studied in OPLA Phase 1. There is greater similarity to the Phase 1 concept in the second method, in which containers filled with short sections of fuel elements are emplaced in boreholes in the galleries.

This study, due for completion in 1995, also considers various design options for the combined disposal of reprocessing waste and spent fuel. This "combined concept" has been subject to exploratory study during the supplementary OPLA research programme (ECN, 1993c). In the disposal concept investigated, the spent fuel originates from a possible enlargement of the nuclear energy potential by 3000 MWe. The reprocessing waste to be disposed of originates from the operations of the existing Dodewaard and Borssele nuclear power stations. As regards technical feasibility, the OPLA study indicates that the chosen disposal technique with boreholes in galleries will not require any drastic modifications to the Phase 1 design. As regards safety, modelling was used to calculate the risk associated with flooding in a disposal mine. It is found that the risk for the technique and waste volume studied here is smaller than 10-6/year.

The exploratory study relating to direct disposal reveals that several feasible disposal techniques are available. The findings of this study match those of the above-mentioned PAE study among others.

17.8 CONCLUSIONS

General

On the basis of the results of the supplementary research programme presented above, the OPLA Committee reached the following statements:

- The supplementary research programme disclosed no phenomena or combinations of phenomena which would a priori lead to rejection of the "disposal of radioactive waste in salt formations" option.
- Insight into the parameters affecting the uncertainties in the risks of disposal has increased strongly; as a result, the safety approach is now based on better confirmed data. It has been possible to further validate, analyse and extend the models and data required for the safety calculations. In this way, substantial advances have been made in determining the bandwidths in the results of Phase 1. Accordingly, the objective of the first theme of the supplementary research programme has been achieved.
- Even after completion of the supplementary programme, a number of major uncertainties remain with regard to definition of the risk-determining features of a repository and the natural barriers, practical validation of the models used in the safety study,

and the consequences of gas formation and radiation damage in rock salt.
- Development of the PROSAsafety method has yielded an extremely useful instrument for scientifically based risk assessment of geological disposal in rock salt formations. In addition, the PROSA approach appears to have a broader application potential.
- Exploratory study of several new aspects, retrievability of disposed-of radioactive waste and direct disposal of spent fuel in rock salt, has demonstrated that integration of these variants will entail engineering design consequences. The associated design modifications appear to be technically feasible; no prohibitive factors were identified in the study.

Earth Scientific Background Studies

From recent research on model development of geological processes, the following conclusions can be drawn:

- Intraplate stress is the major driving force for the initiation of salt diapirism in the North Sea, which is in contrast with the classical theory of a purely gravitational drive of diapirism.
- Salt dissolution rates in Dutch diapirs are positively correlated with the performance of glacial and subglacial processes.
- Results from the FLUVER model suggest that geological barriers comprising salt diapirs and their cover beds in the Netherlands, have not been, and will not be, affected significantly by fluvial erosion in the past 200,000 years and in the next 100,000 years.
- Although the process of subglacial erosion, having created deep tunnel valleys in the North Sea basin, is still not yet fully understood, the results from SUBGLER model studies suggest that these phenomena were formed during the last phase of deglaciation, as a result of overpressurizing Quaternary aquifers by subglacial meltwater.

Geological studies on the underground disposal of long-lasting hazardous waste in many countries have demonstrated the need for a time-dependent geological simulation model for the geological barriers enveloping the disposal site, in which relevant geological processes are integrated and coupled. Promising results of climatic and tectonophysic research indicate that the development of such a barrier model would be feasible in the next decade. The development of an integrated geological barrier model is only feasible if a large concerted multidisciplinary effort, preferably in an international framework, is carried out.

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